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14. ABSTRACT

This project examined coherence with respect to time, space and frequency. As part of our work on this project we developed coherence models which incorporated the environment via scattering and propagation models and performed analysis of experimental SAS data from a variety of systems. This work also explored the usable coherence domain in terms of environmental effects for detection and classification techniques based on coherence. Novel detection and/or classification ideas may result from this systematic look at coherence.

15. SUBJECT TERMS

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Coherence Studies for Synthetic Aperture Sonar

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LONG-TERM GOALS

Researchers have largely been successful in achieving their goals of producing high-resolution imagery with high frequency sonar systems and are now actively working on techniques for expanding the use of these systems in ways that may offer advantages in target detection and classification. Coherent change detection (CCD) looks at temporal coherence between images taken at different times to optimally detect subtle changes in a given scene. Unfortunately, developments such as CCD are proceeding in many cases without a solid understanding of how environmental effects might degrade performance or conversely how environmental knowledge can be used to improve performance. This type of knowledge is absolutely required for these new techniques to be used to fullest advantage in the variety of environments that exist in shallow water areas (or not used at all given limitations imposed by the environment).

Although temporal coherence is an area that is currently receiving much attention, coherence with respect to other variables such as space (angle) or frequency have not as of yet been explored adequately for potential uses in detection and classification. The presence or lack of coherence could prove to be a useful method for detecting man-made targets. Coherence may prove to be more robust than acoustic color template matching as it may be less sensitive to mismatches associated with burial, geometry or with unexpected target shapes or types for which no template exists. As in CCD, looking at coherence in space and frequency is another way to use additional information available in SAS data and not rely solely on information in intensity-only images.

As an overarching theme for the proposed research, therefore, we plan to look at coherence with respect to time, space and frequency as part of our proposed research via development of approximate and/or numerical scattering models and an analysis of real SAS data from a variety of systems to explore the usable coherence domain in terms of environment for techniques based on coherence. It is hoped that novel detection and/or classification ideas may also result in an in-depth and systematic look at coherence.

OBJECTIVES

The importance of the present work lies in the ability to link SAS coherence to measurable environmental properties such as seafloor roughness. In conjunction with sonar system parameters, this link will provide necessary bounds resulting from the environment on the use of coherence as a detection and classification tool as well as suggest other novel ways to use coherence. The direct link between system and environmental parameters via scattering models will allow: performance prediction for different systems based on environmental properties, extrapolation of performance to other systems, and optimization of system parameters such as frequency/bandwidth to the local environment.

Concisely our broad objectives are:

1. Examine relationships of environmental properties of sediment, water column or rock to coherence in time, space, and frequency via analysis of experimental SAS data.
2. Develop and compare predictive models of the relationships between environmental parameters and coherence as a function of frequency, repeat-pass time, etc.

APPROACH

In terms of efficiency, both in the use of common high-quality acoustic data sets that will be collected over the next two years and in the use of common modeling techniques it makes sense to take the opportunity to pursue the two component studies in the same time frame. In the experimental work discussed below, targets are included in the field of view as well, allowing us to test ideas about temporal, angular and frequency coherence differences between target and background. Specifically

Environmental factors affecting temporal coherence in repeat-pass SAS:

As a follow on to our early work on temporal coherence, we propose to examine more fully environmental factors which affect coherence in repeat-pass SAS, including biological and hydrodynamic movement of sediment and changes in water column sounds speed structure. This goal will be achieved through an association with current PIs and projects being performed by the NSWC-Panama City (Tesfaye G-Michael), APL-UW (Kevin Williams), FFI (Roy Hansen), and NRL (Allison Penko) and possibly NURC (Warren Fox). The study will include several components: a background study of predictive biological and hydrodynamic models that may exist; a background study of any relevant acoustic work in measuring or modeling temporal coherence; modeling of coherence as a function of frequency based on physical scattering models; analysis of as much acoustic data (hopefully with ground truth) that we can get our hands on in as many different environments as possible to confront with any developed models; and finally

feeding our results into complementary work being done at NSWC linking changes in coherence to more general models of biology, hydrodynamics, sediment type, etc. We want to feed our results and models of bioturbation caused ripple decay to Allison Penko at NRL to advance her funded 6.2 project "Operational Forecasting the Seafloor Boundary Layer in the Littoral." We would also hope to use her models of ripple formation to address possible factors affecting incoherent change detection (large scale changes in bedforms).

As part of the proposed work we want to specifically look at more data in a more controlled way than we did with the SAX04 data and also include the water column changes in our studies. We plan on doing this with Kevin Williams' SAS rail data in 2013 (we'll provide a thermistor chain for water column sound speed measurements) and also possibly look at CCD data collected by FFI with their HISAS system in Larvik, Norway, during our joint experiment last April. Kevin Williams also plans another study in 2014 in a muddy environment so that we have the potential to look at several different seafloor types including a sandy site, a rocky site and a muddy site. Regular passes will be made with Kevin's rail mounted transmitters as often as every few hours over a time period of as long as a week to fully populate our coherence versus frequency and time curves.

Environmental factors affecting coherence in space and frequency in SAS data.

We want to attack the problem of understanding coherence in angle and frequency using the same experimental data sets as used for the temporal coherence studies, with the addition of data sets from NURC and data collected during SAX04. The NURC data includes rocky seafloor data as well as data from a 'calibrated' rock that has been scanned to get the exact shape which could be used to compare field measurements of coherence to those estimated via scattering models. The SAX04 acoustic data is the same as that studied for temporal coherence and has excellent roughness measurements to use in modeling coherence with physical scattering models such as perturbation theory. Through use of approximate or numerical models it is hoped that we can determine the shape of the angular and frequency coherence functions as a function of driving parameters such as roughness to gain insight into sensitivity. This is basic research and it is hoped that through comparisons between the coherence estimated from acoustic data and models of coherence based on scattering theory we can explore the possibilities of using all the information available from modern SAS systems. Dan Brown would be helping with this component and is also working on a related project on correlation sonars for his dissertation work, "Navigation Sonar System Performance Modeling." Our projects would be complementary, with both requiring physical models of coherence.

WORK COMPLETED

A variety of topics were investigated in FY2014 all of which related to the study of environmental factors affecting temporal coherence in repeat-pass SAS. We have examined the relationships of both water column and sediment properties to temporal coherence via analysis of SAS data collected during field experiments. We have also worked on the development of predictive models for the relationships between these environmental parameters and coherence. Results of previous years' analysis were used in conjunction with a connected project (PI, Shawn Johnson) to devlop methods for simulating temporal changes in complex SAS images between repeat passes. This work was published in an Institute of Acoustics Proceedings. Several of our studies this year involved collaboration with and the use of data provided by several laboratories including the Norwegian Defence Research Establishment (FFI - POC, Roy Hansen) and the Centre for Marine Research and Experimentation (CMRE – POC, Warren Fox). Collaborative papers have also been written with researchers from FFI, NSWC-Panama City Detachment (NSWC-PCD), Defence Research and Development Canada, and the Georgia Tech Research Insititute (GTRI). With graduate student Dan Brown we have also spent time exploring methods for modeling spatial coherence of the scattered acoustic field and a paper resulted from this work.

As noted in our objectives, we have invested a portion of our time in FY14 to the study of water column effects on repeat-pass coherence. Our work this year included the completion and publication of a joint paper with FFI in the IEEE Journal of Oceanic Engineering and a joint paper with FFI and GTRI in an Institute of Acoustics Proceedings. This work was a continuation of an effort begun in FY13 on data collected by FFI in October 2012, with the CMRE during the ARISE'12 trials from the NATO research vessel Alliance, off of Elba island, Italy. During this trial, data was collected using a HUGIN AUV with interferometric SAS. Large visible structures in the SAS images and in the SAS bathymetries were caused by features in the water column that formed after breaking internal wave events. These features mimicked perfectly what one would expect for real seafloor features both in terms of intensity and interferometrically derived bathymetry. Changes observed in acoustic intensity and phase seen in the SAS data were caused by refraction effects as the acoustic field interacted with the lower sound speed structure of the bolus. Our interpretation of this phenomenon was based on the simple idea that the variation in backscattered intensity from the seabed was caused by a focusing of sound by the bolus and errors in bathymetry by the changes in propagation angle as the acoustic energy moves through the lower sound speed bolus. In the IEEE JOE paper a ray model was used to simulate the effects of the bolus on the acoustic field incident on the bottom and compared favourably to SAS data. Several methods were examined to answer the question of how to identify this effect as being due to a change in the water column and not the seafloor. Another open question concerns the ubiquity of water column effects on SAS imagery and texture in general.

Other work peformed this year looked at the effects of turbulent water column sound speed structure on residual phase seen in the coherence in repeat-pass data analyzed by NSWC-PCD. It was seen in this data that, after all navigation and motion differences between two complex images taken 2 hours apart were removed, there was still residual phase observed. The structure of the residual phase was large scale and random and was not consistent with errors which may have been due to the bathymetry. A possible cause was identified as turbulent water column sound speed structure. Although the residual phase seen in the NSWC-PCD data was not large enough to effect the detection of changes between the two images the effect could be a problem in areas with stronger sound speed fluctuations (e.g., tidally influenced areas or during storms in shallow water areas). Example results of this work will be shown in the next section.

The results of the work performed this year may be important for: 1) for understanding and possibly exploiting temporal and spatial coherence in SAS systems and 2) for developing methods to invert for seafloor and water column parameters impacting change detection using SAS systems.

RESULTS

In a paper recently submitted to IEEE Journal of Oceanic Engineering [Image-based automated change detection for synthetic aperture sonar, T. G-Michael, B. Marchand, J.D. Tucker, D.D. Sternlicht, T.M. Marston and M.R. Azimi-Sadjadi], data and analysis was presented that dealt with repeat pass coherent change detection. The experiment performed by NSWC-PCD took place off of Panama City and consisted of repeat passes of a SAS system over hours to days at several different sites. Figure 1 displays an example of two SAS images taken 2 hours apart and the residual phase which remains after all navigation and motion induced phase changes have been removed. Large-scale structure can be seen in the plot of residual phase and show phase changes of up to +/- $\pi/3$. It is postulated that these phase changes are a result of differences in the random turbulent sound speed structure that existed between the two passes of the SAS system. Although this structure exists on each individual pass DPCA navigation removes this structure along with non-linear motion (DPCA treats all phase change as equivalent whether due to motion or sound speed differences). So, although the structure doesn't manifest in anyway in a single image it will when comparing two complex images taken at different times. Higher frequencies (smaller wavelengths) will show this effect more strongly than lower frequencies (longer wavelengths).

The effect on phase was modeled by assuming a Kolmogorov-Von Karman spectrum description of the sound speed spatial structure. This spectrum is power law in form and is very commonly used in describing turbulence induced structure with larger features exhibiting stronger fluctuations. Figure 2 displays a realization of the sound speed structure with a Kolmogorov spectrum and predictions from a phase screen model of the residual phase which would be seen between two 200 kHz SAS image collected through two different realizations of turbulent sound speed structure. It should be noted that even though small, the sound speed fluctuations used for this simulation produced phase

differences comparable to those seen in the real experimental data of Figure 1. Larger sounds speed fluctuations would be expected in a variety of environments including areas with tidal influence and shallow-water areas during storm events.

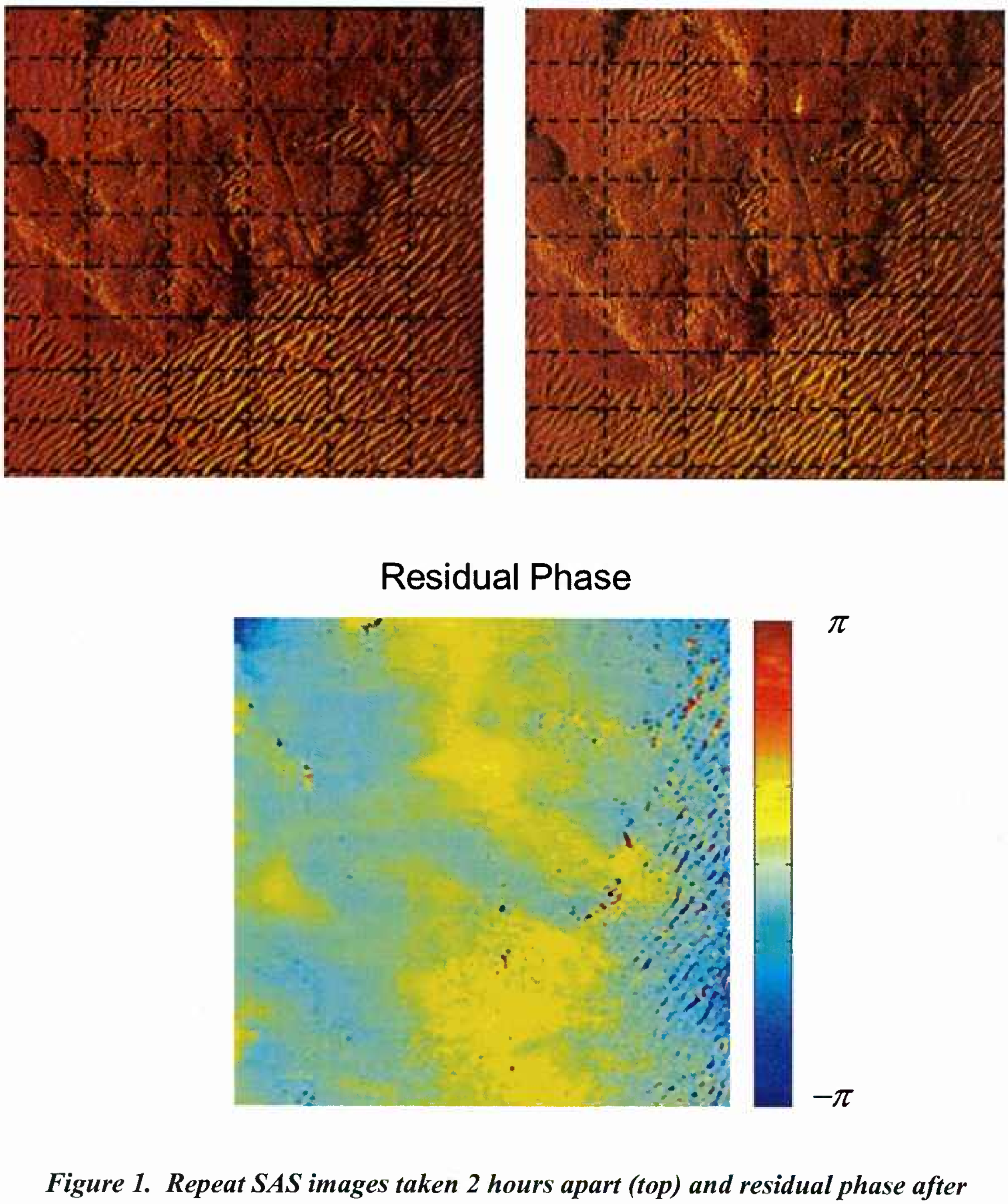

Figure 1. Repeat SAS images taken 2 hours apart (top) and residual phase after navigation and motion induced changes in phase have been removed (bottom). Images are from a paper by T. G-Michael, B. Marchand, J.D. Tucker, D.D. Sternlicht, T.M. Marston and M.R. Azimi-Sadjadi submitted to IEEE J. of Ocean. Eng., "Image-based automated change detection for synthetic aperture sonar".

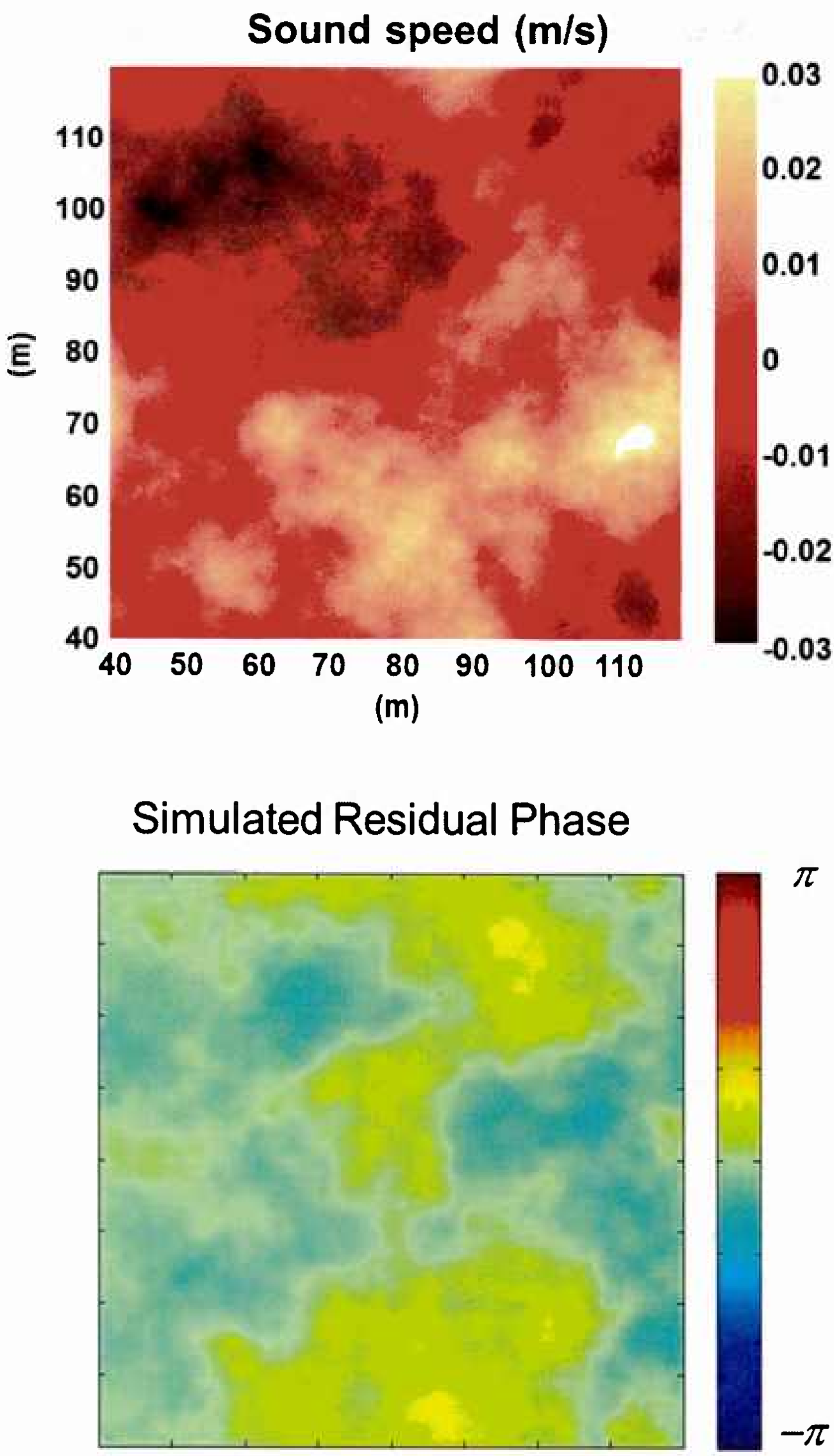

Figure 2. Spatial structure of sound speed modeled using Kolmogorov – Von Karman turbulence spectra (top) and phase differences predicted for 200 kHz SAS data taken with two realizations using a phase screen model.

Based in our study this year on this phenomenon we believe that important characteristics of internal waves and boluses on the inner shelf such as size, volume and speed, can be extracted from SAS data precisely because of the sensitivity of the sonar to changes in the refractive index associated with these features. These features are very difficult or impossible to distinguish from a real seafloor feature in a single pass and may be prevelent in areas with a strong thermocline. The effects of turbulent sound speed structure also cannot be ignored when performing coherent change detection with high-frequency systems especially in areas where turbulence is common. Advancing our basic understanding of the effects of oceanographic phenomena on seafloor imaging sonars should allow for development of techniques to mitigate such effects on naval sonar systems. Additionally, based on our work this year, it is suggested that current SAS systems be used to remotely sense and invert for oceangraphic properties of internal waves and turbulence.

IMPACT/APPLICATIONS

SAS coherence research is providing an improved understanding of the environmental parameters that affect high-frequency imaging systems. This study is leading to methods for modeling and predicting these environmental effects that may be used to mitigate negative impact of these effects on detection and classification of targets on or near the seafloor in shallow water. Knowledge gained will help in the development of simulation tools, adaptive systems for sonar systems and rapid environmental assessment techniques for estimating environmental parameters for a given area.

TRANSITIONS

Discussions are under way to include models into the SAS simulation capabilities of PC-SWAT which is developed and maintained at NSWC-Panama City. We are also actively collaborating with Allison Penko at NRL-Stennis to include our models of temporal seafloor changes in her predictive seafloor roughness models as well as using her ripple formation models in our own SAS image simulation tools.

RELATED PROJECTS

This work is being performed cooperatively with Shawn F. Johnson [APL-JHU] under ONR Grant N00014-13-1-0020.

PUBLICATIONS FY14

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